THE KARLSRUHE NUCLIDE CHART: AN EDUCATIONAL TOOL FOR THE NUCLEAR SCIENCE COMMUNITY

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ABSTRACT

A new 7th edition of the Karlsruhe Nuclide Chart was published in 2006. For almost 50 years, it has provided scientists and students with structured and accurate decay data on all known radionuclides. The Chart is of great didactic value in education and training in the nuclear sciences and provides a record of scientific progress on the discovery of new elements, nuclides, and decay modes.

1. Introduction

The Karlsruhe Nuclide Chart (KNC) is a unique tool for the nuclear science community that presents structured and accurate information on the radioactive decay of nuclides. In the 1950s, in order to meet the demand for professional training and education in developing fields of nuclear engineering and radiochemistry, the Radiochemistry Institute in the Karlsruhe Nuclear Research Centre held courses on radiochemical isotopes. The Karlsruhe Nuclide Chart was created within the scope of this teaching activity. Through the successive editions dating back to 1958, the chart has evolved to reflect scientific progress and breakthroughs. The discovery of new elements, modes of decay, and nuclides far from the stability region is reflected in the various chart editions. The latest 7th edition (2006) [1,2] contains new and updated decay data on 619 nuclides.

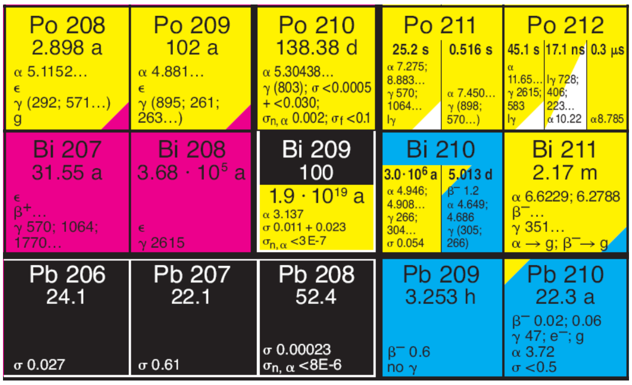

Fig 1. Section of the Karlsruhe Nuclide Chart, revised 7th edition 2007.

The Karlsruhe Nuclide Chart is based upon the proton-neutron model of the nucleus and is basically a plot of the number of protons versus the number of neutrons in stable and unstable nuclei. In contrast to many other data compilations and databases [3] which include calculated or theoretically predicted values, the data in the Karlsruhe Nuclide Chart is based primarily on experimental work. For example, nuclides are included in the chart only if the half-life or the mass has been measured or the nuclide has been clearly identified. As the chart was not developed for a specific purpose and with specific data needs (e.g. nuclear reactor community), the presented data is of general use in health physics and radiation protection, nuclear and radiochemistry, nuclear medicine, astrophysics, etc.

The current 7th edition [1,2] contains nuclear data on 2962 experimentally observed nuclides and 692 isomers. The accompanying brochure includes a history and overview of nuclear science. The multi-lingual "Explanation of the Chart of the Nuclides" has been extended from the original four languages (English, German, French, and Spanish) to include Chinese and Russian. Recently, a KNC wiki page [2] has been created to provide users with additional information. A dedicated forum is also available [1], and a FAQ page is under development.

2. Use of the Karlsruhe Nuclide Chart: some examples

Each nuclide is represented by a box containing basic nuclear data as shown in Figs.1 & 2. This data is composed of general decay data with half-life, decay modes and energies of decay radiations.

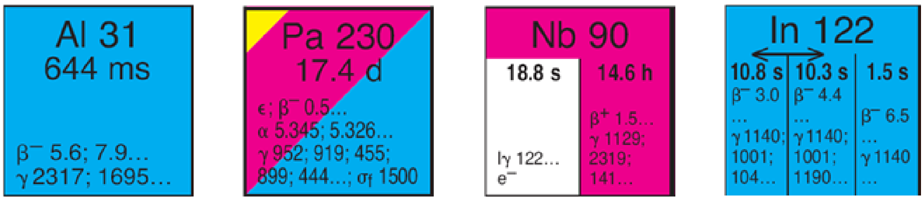

Fig 2. Nuclide representation in the Karlsruhe Nuclide Chart.

An important characteristic of the boxes is the use of colours to denote the modes of decay. There are in total 9 main decay modes, namely proton (orange), α (yellow), β^- (blue), neutron (light blue) and cluster emission (violet), β^+-emission and ε electron capture (both red), spontaneous fission (green) and isomeric transition (white). Some of these modes can have multi-particle emission. As a result of the decay process, a daughter nuclide will result. The main radioactive decay processes are shown in Fig. 3.
The branching ratios of the decay modes are not given explicitly in the chart, but are indicated by the relative sizes of the coloured areas. Pure decay modes, with a branching ratio of 100%, are indicated by a single colour. For nuclides with two decay modes, a small triangle indicates a branching ratio smaller than 5%, for example 2.5% or 10^{-7}%. The major mode has conversely a branching ratio greater than 95%. If the branching ratio of the minor mode is in the range 5 to 50%, and that of the major mode in the range 50 to 95%, the box is divided into two equally sized triangles. Three decay modes are also possible, with similar minor decay mode conventions.
The types of radiation emitted (e.g. α, β^-, etc.) are presented on the chart together with the energies of the most important emissions. The main gamma lines are presented in order of decreasing probability. Where the γ corresponds to a transition following β-delayed particle emission, the γ-energy is followed by an asterisk.
Some examples of nuclides from the KNC are shown in Fig. 2. The first nuclide shown, ^{31}Al (denoted "Al 31" in the nuclide chart), has a half-life of 644 ms. The colour blue indicates β^- decay. The fact that the box is entirely blue implies that the branching ratio for β^- decay is 100%. The β^- particle energies with the highest emission probability (5.6 MeV) and highest end-point energy (7.9 MeV) are given. These particle emissions will generally lead to daughter nuclides in excited states which de-excite through gamma emission. The resulting gamma energies are shown in order of decreasing emission probability, i.e. 2317 keV and 1695 keV. Since they result from β^- decays, these gammas are associated with the parent ^{31}Al rather than the daughter.
The second nuclide shown, ^{230}Pa, has a half-life of 17.4 d. The three colours indicate three modes of decay: yellow: α-decay, red: ε/β^+-decay, and blue: β^--decay. The small yellow triangle indicates that the α-decay branching ratio is less than 5%. The red and blue coloured regions indicate branching ratios greater than 5% for electron capture ε (red colour) and β^- emission (blue colour). The fact that electron capture has a higher branching ratio than β^--decay is indicated by the text "ε; β^-" (i.e. electron capture is first, β^- second).
The third nuclide, ^{90}Nb, shows another feature - an isomeric state of the same nuclide. The ground state (14.6 h half-life) is located on the right hand side and the isomeric metastable

state (18.8 s half-life) to the left. The ground state, which is coloured red, decays by positron emission (β^+) with a branching ratio of 100%. The metastable state ^{90m}Nb decays by isomeric transition Iγ (indicated by white) also with a branching ratio of 100%. Emission of conversion electrons, denoted by e^-, is specified only if the emission probability for electrons is higher than that of the gammas. This is the case for ^{90m}Nb. Note also that metastable states for isomeric transitions are only indicated if the half-life is greater than 1 s.
The fourth nuclide shown in Fig.2, ^{122}In, is an example of a nuclide which has more than one isomeric state. ^{122}In has two metastable states indicated by ^{122m1}In and ^{122m2}In. All three states i.e. the ground state and the two isomeric states decay by pure β^- emission indicated by the colour blue. Where there is uncertainty on the assignment of the properties to a particular metastable or ground state, this is indicated by the double arrow shown in Fig. 2.

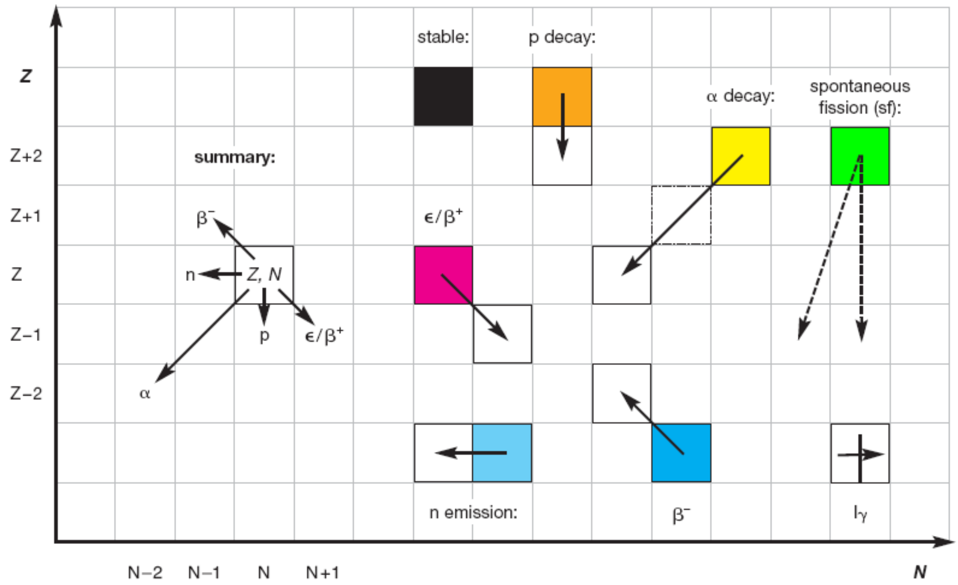

Fig 3. Radioactive decay processes on the nuclide chart. A nuclide parent with coordinates Z, N transforms to a daughter nuclide through the decay processes shown [1,2].

3. The Karlsruhe Nuclide Chart: A Record of Progress in Nuclear Science

Since the discovery of natural radioactivity by Becquerel in 1896 and isotopes by Soddy in 1913, improvements in scientific techniques have led to the discovery of artificial elements, new nuclides and decay modes. This progress has been reflected in the various editions of the KNC as shown in Fig.4. Some examples are described in the following sections.

3.1 New Elements and Nuclides

The first transuranium elements were synthesized with successive neutron capture reactions in long-term irradiation in high flux reactors [4]. Through the work of Seaborg and colleagues eight artificial elements with Z = 93 (Neptunium)-100 (Fermium) were produced in the period up to around 1955. Elements heavier than Fermium were synthesized using projectiles of ions (see below) which resulted in "hot" compound nuclei which then decay via neutron and gamma emission. In general, these "hot" compound nuclei undergo fission into two fragments - neutron emission occurs only in about 1% of the reactions. The synthesis of elements heavier than 106 (seaborgium Sg) became possible only after the discovery of the so-called "cold-fusion reactions". In these reactions, targets of "magic" nuclei, e.g. ^{208}Pb and ^{209}Bi, were bombarded by ions heavier that argon. The resulting compound nucleus, which has a much lower excitation energy, decays through the emission of one or two neutrons.
Element 101, Mendelevium, the ninth transuranium element to be discovered, was first identified in 1955 as a result of the bombardment of ^{253}Es with helium ions. Sixteen isotopes

of Mendelevium are listed in the latest edition of the KNC. *Element 107*, Bohrium: In 1976 scientists at Dubna announced they had synthesized the element by bombarding ^{209}Bi with heavy nuclei of ^{54}Cr. *Element 108*: The element 108, Hassium Hs, was first synthesized in 1984. A lead target was bombarded with ^{58}Fe nuclei to produce 3 atoms of ^{265}Hs. *Element 118*: The discovery of element 118 was announced in Oct. 2006. Three nuclei were observed via collisions of ^{249}Cf and ^{48}Ca ions [4].

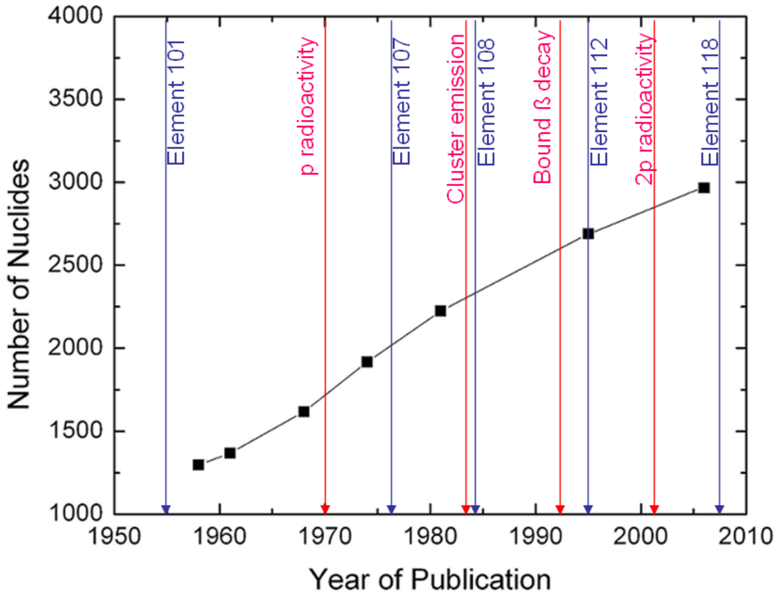

Fig 4. Number of nuclides in the various editions of the Karlsruhe Nuclide Chart.
A timeline of related major discoveries is also shown.

The recent discovery of two new neutron-rich nuclides [5], ^{40}Mg and ^{42}Al, has provided additional insight into the exact location of the neutron drip-line. The drip-line is the limit of how many neutrons can bind to a given number of protons. Because of the interplay between single particle and collective quantum effects, the drip-line can only be predicted for the lightest elements.

3.2 New Decay Modes

Proton Emission: proton emission was first observed in 1970 [6] with the nuclide ^{53m}Co. There are over sixty proton emitters reported in the Karlsruhe Nuclide Chart. This is an active area of research as it provides a unique way of mapping the proton drip-line.
Cluster Emission: An intermediate decay process, between alpha decay and spontaneous fission, was discovered by Rose and Jones in 1984. This "new kind of natural radioactivity" [7], consists in the emission of a light nuclide such as: ^{14}C, ^{20}O, ^{23}F, ^{24}Ne, ^{25}Ne, ^{28}Mg, ^{34}Si. There are currently 16 cluster emission nuclides cited in the chart.
Bound Beta Decay β_b: when a stable atom is fully ionised, the resulting ion may be unstable. These nuclei give rise to a special kind of β^- emission in which an electron is liberated from the nucleus, through transformation of a neutron to a proton, and captured into one of the empty energy shells of the atom. This “bound beta decay” was observed for the first time in 1992 [8]. There are now four such isotopes known in nature: ^{163}Dy, ^{187}Re, ^{193}Ir, and ^{205}Tl. The isotope ^{187}Re is included because of its extremely long half-life (5×10^{10} y). Bound beta decay was first observed with highly charged ions of the stable nuclides ^{163}Dy and ^{187}Re provided by the synchrotron and stored in the storage cooler ring at GSI Darmstadt. The ionised $[^{163}\text{Dy}]^{66+}$ is observed to decay with a half-life of 47 d by β_b emission to ^{163}Ho. For the almost stable ^{187}Re, the fully ionised $[^{187}\text{Re}]^{75+}$ shows a decrease in the half-life of 9 orders of magnitude from 5×10^{10}y to 32.9y. In addition to the ^{163}Dy/^{163}Ho transmutation under extreme conditions, other such reaction pairs are ^{205}Tl/ ^{205}Pb and ^{193}Ir/^{193}Pt and these may have an impact in stellar nucleo-synthesis where terrestrial and stellar half-lives may be different.

Two-Proton Radioactivity: Two-proton radioactivity was first observed in 2002 [9,10]. The first direct observation of two proton decay emission in the decay of ^{45}Fe was reported in 2007 [11,12] and is shown in Fig.5 (from [12]).

Beta-delayed Proton Emission: For neutron deficient nuclides, there exists the possibility of proton emission from excited states populated in the daughter nuclide via a β-decay. β^--delayed two-proton emission was first reported in 1983 in the decay of ^{22}Al and ^{26}P. The first observation of β-delayed three proton emisison in ^{45}Fe was reported in 2007 [13] through the use of a newly developed ionisation chamber. The first photographic recording this process is shown in Fig.5. Through these new experimental observations, the information on the nuclide ^{45}Fe in the Karlsruhe Nuclide Chart will be updated in the next edition. The updated nuclide box, reflecting these discoveries, is also shown in Fig.5.

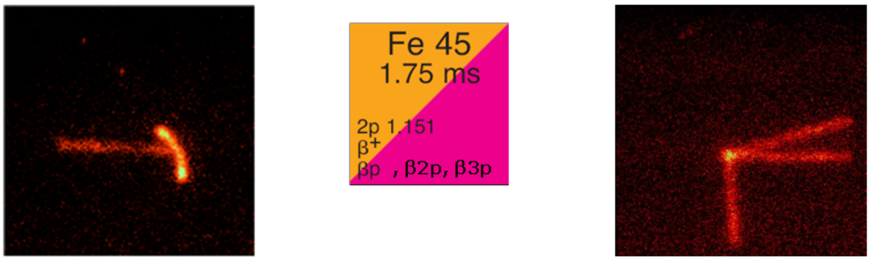

Fig 5. Camera recording of 2p and β3p decay events in ^{45}Fe. *Left:* A track of a ^{45}Fe ion entering from left. The two short tracks are protons of ~0.6 MeV. (image courtesy of M. Pfützner). *Right:* three tracks of protons following the β^- decay (Reprinted with permission K. Miernik, et al., Phys. Rev. C 76, 041304 (2007). Copyright (2007) by the American Physical Society). *Centre:* updated nuclide information for ^{45}Fe shown in the nuclide chart.

4. Conclusions & Future Work

The 7th edition of the Karlsruhe Nuclide Chart has been produced by the European Commission's Joint Research Centre at the Institute for Transuranium Elements. Support for the current and future editions is ongoing to reflect scientific progress in nuclear science. In the future, new versions of the Chart will be available in electronic form (e.g. CD ROM, Web portal) in addition to the paper-based version in line with developments in information technology.

5. References

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